Gas Dynamical Simulations of the Large and Little Homunculus Nebulae of η Carinae

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ABSTRACT

We here present two-dimensional, time-dependent radiatively cooling hydrodynamical simulations of the large and little Homunculus nebulae around η Carinae. We employ an alternative scenario to previous interacting stellar wind models which is supported by both theoretical and observational evidence, where a non-spherical outburst wind (with a latitudinal velocity dependence that matches the observations of the large Homunculus), which is expelled for 20 years, interacts with a pre-eruptive slow wind also with a toroidal density distribution, but with a much smaller equator-to-polar density contrast than that assumed in previous models. A second eruptive wind with spherical shape is ejected about 50 years after the first outburst, and causes the development of the little internal nebula. We find that, as a result of an appropriate combination of the parameters that control the degree of asymmetry of the interacting winds, we are able to produce not only the structure and kinematics of both Homunculus, but also the high-velocity equatorial ejecta. These arise from the impact between the non-spherical outburst and the pre-outburst winds in the equatorial plane.

Subject headings: hydrodynamics — ISM — shock waves — stars: individual (η Car) — stars: winds, outflows

1. Introduction

The dusty large (16" long) bipolar Homunculus ejecta around η Car is a hollow reflection nebula (e.g., Smith et al. 2003a and references therein) that was produced by the 20 year Great Eruption of the star, from $\sim$1840 to 1860. Its axis is inclined $\sim 45^o$ to the line of sight (Davidson et al. 2001), and at a distance of $\sim$2.3 kpc, it has a total physical size $\sim 6 \times 10^{17}$ cm. The hot features observed outside the bipolar nebula were very probably ejected earlier in episodic events before the major eruption (Walborn et al. 1978; Weis et al. 2001). Recently, an inner bipolar emission nebula has been also discovered embedded within the larger Homunculus (extending from -2" to $+2$"

across the star) which may have been originated from a minor eruption event in the 1890s, i.e., $\sim$50 years after the formation of the larger Homunculus (Ishibashi et al. 2003). This little Homunculus seems to follow approximately the shape of the larger one. Observations also evidence the existence of ejecta in the equatorial region that may contain material from both the 1890 eruption and the great eruption in the 1840s (Davidson et al. 2001). The velocity of this material obtained from Hα profiles may reach velocities $\sim 400 - 750$ km s^{-1} (Smith et al. 2003a).

As an extreme luminous blue variable star (LBV), η Car loses copious amounts of mass in form of quasi-steady winds punctuated by eruptive events where the mass loss may increase by at least an order of magnitude in short periods of time (Maeder 1989; Pasquali et al. 1997). Currently, the dominant velocities in the expanding Homunculus are 400 to 600 km s^{-1}, but some faster material (~ 1000 km s^{-1}) has been detected in the poles (e.g., Smith et al. 2003a),

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and the mass-loss rate is $\sim 10^{-4} - 10^{-3}$ M$_\odot$ yr^{-1} (Humphreys & Davidson 1994, Hillier et al. 2001; Corcoran et al. 2001; Soker 2001). The inner bipolar nebula, produced during the 1890s eruption, has a peak velocity ~ 300 km s^{-1} and a total estimated mass ~ 0.1 M$_\odot$ (Ishibashi et al. 2003).

It has been previously suggested that the shaping of the η Car nebulae could be explained by a colliding wind binary star model. Soker (2001), for example, has argued that the companion star could divert the wind blown by the primary star, by accreting from the wind and by blowing its own collimated fast wind that could have, in turn, played a role in the formation of the Homunculus lobes. A strong argument against a companion star dominating the wind structure is that it appears to be predominantly symmetric, as indicated by recent STIS spectral observations in several positions along the Homunculus (Smith et al. 2003a). These show the same latitudinal dependence for the velocities in both hemispheres and both sides of the polar axis, and the same P Cygni absorption in hydrogen lines on either side of the poles. Although a colliding wind binary model cannot be disregarded at the present, we here assume that the shaping of η Car nebulae is dominated by the primary star's wind.

As noticed by Smith et al. (2003a), the high velocities seen in reflected light from the polar lobes give a first direct evidence that the polar axis of the Homunculus is aligned with the rotation axis of the central star. This has important consequences for the formation of the bipolar lobes and the equatorial ejecta around η Car, as it may be an indication that axial symmetry and the ejection mechanism during the Great Eruption were directly linked to the central star's rotation. Also, the observed latitudinal variations in H and HeI lines revealing that the speed, density and ionization in η Car wind are non-spherical nearby the star, may be an indication that the stellar wind is inherently non-spherical.

In previous work, Frank et al. (1995) have performed low resolution two-dimensional numerical simulations of the large Homunculus of η Car, adopting an interacting stellar wind scenario wherein a spherical fast wind expands into a non-spherical (toroidal) slow, dense wind previously ejected from the star. They found that the Homunculus morphology could be reproduced with an equator-to-polar density ratio ~ 200, which would imply the existence of a very dense toroidal environment surrounding the nebula. Langer et al. (1999), have assumed a variant of this scenario including the effects of stellar rotation. Using the wind-compressed model of Bjorkman & Cassinelli (1992), they showed that a strong equator-to-pole density contrast could have formed during the great outburst in the 1840s if the star was close to the Eddington luminosity limit. Under this circumstance, the centrifugal and radiative forces must balance gravity at the equator, and a strong non-spherical mass loss should occur deflecting the wind streamlines towards the equator. In this model, a spherical, fast post-outburst wind produces the bipolar bubble through interaction with the toroidal outburst flow. In addition to forming lobes with an approximate shape to the observed Homunculus, this numerical model (which has included the effects of time-dependent radiative cooling) has revealed the development of small fingers at the shell surface caused by Vishniac type instabilities.

Although these previous models are partially successful at reproducing the basic shape of the large Homunculus nebula, they both rely on the presence of a thick torus around the Homunculus nebula (which is very dense in the equatorial region). Observations however, indicate only the presence of a faint nebulosity surrounding the large Homunculus. To overcome this difficulty, more recently Frank et al. (1998), and Dwarkadas & Balick (1999) have proposed alternative models. Assuming an inverted scenario, in which a $non - spherical$ fast wind expands into a previously deposited $isotropic$ slow wind, Frank et al. (1998) have found that they are able to reproduce strongly bipolar outflows with polar caps that can be denser than the lobes' flanks. However, like the previous ones, this model is unable to produce the equatorial ejecta. Dwarkadas & Balick (1998), on the other hand, have replaced the thick torus of the previous models by a small and dense, near-nuclear toroidal ring. This also manages to provide some collimation of the spherical wind ejected during the Great Eruption. Besides, in the presence of radiative cooling, the ring is completely destroyed by the impact of the wind, and the authors have claimed that this fragmentation of the ring could help to explain the equatorial ejecta. A

potential problem with this interpretation is that their model predicts velocities for the fragments that are too small ($\sim 50 - 100$ km s^{-1}) compared to the observed ones in the outer parts of the ejecta (e.g., Smith et al. 2003a).

A successful modeling of the formation of the large and little Homunculus nebulae around η Car should account for both the bipolar morphology and the equatorial ejecta. We here present results of numerical simulations that consider an alternative scenario to the interacting stellar winds models above, in which a fast, non-spherical wind is ejected for 20 years (with a latitudinal velocity dependence that matches the observations in the large Homunculus), interacts with a pre-outburst slow wind also with a toroidal density distribution, but with a much smaller equator-to-polar density contrast than that assumed in previous models. A second eruptive wind with spherical shape is ejected about 50 years after the first outburst, and causes the development of the little internal nebula. We find that, as a result of an appropriate combination of the parameters that control the degree of asymmetry of the interacting winds, this model is able to produce not only the structure of both Homunculus nebulae, but also the equatorial ejecta (see below). [3]

We have carried out several hydrodynamical simulations considering various possible scenarios for the degree of asymmetry of the interacting winds, but here, we will present only the model that has best matched the observations. A more detailed description of the other models will be presented in a forthcoming paper (Gonzalez, de Gouveia Dal Pino, Raga & Velazquez 2003). In contrast to the previous works, our simulations compute explicitly the time dependent radiative cooling of the gas including several atomic and ionic species, which allow for a more realistic evaluation of its effects on the flow.

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[3]We note that there is a number of proposed mechanisms in the literature that predict the development of intrinsically non-spherical winds coming out from rotating LBV stars (see, e.g., Bjorkman & Cassinelli 1992; Lamers & Pauldrach 1991; Owocki et al. 1996, 1998).

2. Numerical Method, Initial Physical Conditions, and Results

In order to investigate the winds' interaction, we have performed gasdynamic simulations using a modified two-dimensional version of the Yguazú-a adaptive grid code originally developed by Raga et al. (2000; see also Raga et al. 2002, Masciadri et al. 2002, Velázquez et al. 2003). This code integrates the hydrodynamic equations explicitly accounting for the radiative cooling together with a set of continuity equations for several atomic/ionic species employing the flux-vector splitting algorithm of Van Leer (1982). The following species have been considered: H I, H II, He I, He II, He III, C II, C III, C IV, O I, O II, and O III. The calculations were performed on a five-level, binary adaptive grid with a maximum resolution along the x and y axes of 7.81×10^{14} cm. The computational domain extends over $(4 \times 10^{17}) \times (4 \times 10^{17})$ cm, corresponding to 512×512 grid points at the highest resolution grid level.

We assume that a light, hot gaseous toroidal distribution was formed around η Car prior to the Great Eruption of $\sim$1840 (e.g., Weis 2001). To produce it, a slow and steady wind is assumed to emanate from the stellar surface into the ambient medium (with initial temperature $T_a = 100$ K and number density $n_a = 10^{-3}$cm^{-3}), with the following properties (see Frank et al. 1995),

$$n = n_0 \left(\frac{r_0}{r} \right)^2 \frac{1}{F_\theta}, \qquad (1)$$

$$v = v_0 F_\theta, \qquad (2)$$

where r_0 is the injection radius, v_0 and n_0 are the velocity and the number density at the pole, respectively. We have considered a similar function to that adopted by Frank et al. (1995, 1998) to produce a smooth variation in the wind density and velocity from the equator to the pole, $F_\theta = 1 - \alpha[(1 - e^{-2\beta sin^2\theta})/(1 - e^{-2\beta})]$, where θ is the polar angle, the parameter β controls the shape of the wind and α the pole-to-equator density and velocity contrasts. The density and velocity angular dependence in equations (1) and (2), respectively, imply a constant mass-loss rate ($\dot{M} \propto n\,v$) as a function of the angle.

We have assumed for the pre-eruptive wind a mass loss rate $\dot{M} = 10^{-3}\ M_\odot$ yr^{-1}; $v_0 = 250$ km

s^{-1}; $\alpha = 0.9$; $\beta = 1.5$; $r_0 = 1 \times 10^{16}$ cm; and initial temperature $T_0 = 10^4$ K. When the slow wind reaches the edge of the computational domain in the polar direction (y-axis), a non-spherical outburst wind is turned on, for 20 years, to produce the Great Eruption, with $\dot{M} \simeq 7 \times 10^{-2} M_\odot$ yr^{-1}; $v_0 = 715$ km s^{-1}; and $T_0 = 10^4$ K. For simplicity, we have adopted the same functional dependence $[F(\theta)]$ as above to compute the velocity and density angular variations in this wind, but with different values for α and β (0.78 and 0.3, respectively). These values were obtained from the best fit of equation (2) to the observed latitudinal variation of the expansion velocity of the large Homunculus (Smith 2002; Davidson et al. 2001). After 20 years, a third wind with the same conditions of the original slow wind resumes for 30 years and then, another outburst (which was assumed, for simplicity, to be spherical) is allowed to occur for about 10 years with $\dot{M} = 10^{-2} M_\odot$ yr^{-1}; and $v_0 = 317$ km s^{-1}, after which the original slow wind again resumes. The adopted values of α and β for the slow pre-outburst wind imply a much smaller (larger) equator-to-pole density (velocity) contrast ($= 10$) than that used by Frank et al. (1995). This results a fainter and lighter toroidal envelope around the large Homunculus, as required by the observations.

Figures 1 and 2 depict the results of this simulation with the interaction of the five winds above. We notice that two bipolar expanding shells develop both with shapes and kinematics similar to the large and the little Homunculus. As in previous calculations (e.g., Frank et al. 1995, 1998), we find that during the 160 years of evolution, the momentum flux is dominated by the outbursts, so that the post-outburst slow winds have no significant effect on the formation of the Homunculus structures. In the case of the outer Homunculus, since its mass-loss rate is almost an order of magnitude larger than that of the pre-outburst wind, it initially expands almost ballistically (in the polar direction), without being much decelerated by the pre-outburst slow wind, and retains most of the non-sphericity imprinted in it near the star, as observed. In the equatorial direction, this first outburst wind reaches the pre-eruptive toroid when its shock front is still within the computational domain. The impact of the two fronts (at $t \simeq 100$ yr after the great eruption; see Fig. 1c) causes the formation of a faint equatorial ejection that could explain the outer parts of the observed equatorial skirt in η Car (Fig. 1d). This ejection moves with a mean velocity $\simeq 700$ km s^{-1}, therefore in qualitative agreement with the observations (Smith et al. 2003a).

The internal bubble that develops from the impact of the second (spherical) outburst with a pre-outburst wind ejected with the same characteristics of the first slow wind (Fig. 1b), soon acquires a bipolar shape (Fig. 1c) which is very similar to that implied from the observations of the little Homunculus with an expansion velocity ~ 300 km s^{-1} (Ishibashi et al. 2003).

The analysis of the results at the outer Homunculus shows that a double-shock structure has developed with an outward moving shock that sweeps the material of the precursor wind and an inward shock that decelerates the outburst wind material coming behind. A thin dense and cold shell develops at the edge of the nebula as a result of the strong compression that follows the radiative cooling of the shocked material behind both shocks. For a strong shock (with $v_s > 80$ km s^{-1}), the radiative cooling time for an one-dimensional shock is given by $t_c \simeq 320$yr $v_{s,100}^{1.12} \rho_{pre,-22}^{-1}$, where $v_{s,100}$ is the shock speed in units of 100 km s^{-1} and ρ_{pre} is the pre-shock densitiy in units of 10^{-22} g cm^{-3} (Hartigan, Raymond & Hartmann 1987; Gonzalez 2002). At the poles, the inward shock speed in the simulation is $v_c \simeq 80$ km s^{-1}, and $\rho_{pre} \simeq 5.1 \times 10^{-20}$ g cm^{-3}. This implies $t_c \simeq 0.5$ yr, which is very short compared to the age of the large Homunculus bubble (~ 160 yr), and results in very small cooling distance behind the inner shock that can be estimated from $d_c \simeq 3.7 \times 10^{14}$ cm $v_{s,100}^{4.73} \rho_{pre,-22}^{-1}$ (Hartigan, Raymond & Hartmann 1987), or $d_c \simeq 2 \times 10^{11}$ cm behind the inward shock. This value qualitatively explains the narrowness of the cold thin shell seen in the simulations (Fig. 1), which, at $t = 160$ yr, has a temperature ~ 6000 K and a density 3×10^{-19} g cm^{-3}. Behind the outward shock, on the other hand, the smaller pre-shock density ($\rho_{pre} \simeq 2.1 \times 10^{-21}$ g cm^{-3}) and the higher shock speed ($v_c \simeq 400$ km s^{-1}) produce a larger cooling time ($t_c \simeq 69$ yr) and, as a result, a thicker and hotter polar cap with $d_c \simeq 10^{16}$ cm (according to the equation above), and $T \simeq 1.6 \times 10^4$ K and $\rho \simeq 2.1 \times 10^{-21}$g cm^{-3} (as obtained from the simulations in Fig.

1). Despite the approximations involved in the evaluation of the cooling distance above, it is only a factor three smaller than the thickness of the outer shell obtained from the simulations which is $\sim 3.5 \times 10^{16}$ cm. This value is in turn, comparable to the observations that indicate a radial thickness of the outer Homunculus $\sim 1'' = 2500$ AU at the poles (Smith et al. 2003a).

A similar analysis for the expanding shell of the inner Homunculus shows that its thickness at the poles (obtained from the simulations) is $\sim 10^{16}$ cm.

3. Discussion and Conclusions

The results of our 2-D hydrodynamical simulations involving the interaction of five winds with different initial conditions indicate that the shape and kinematics of the large Homunculus of η Car can result from the interaction between fast and slow intrinsically $non-spherical$ winds. This model is a variant of previous interacting wind scenarios that have assumed either fast spherical winds interacting with a dense and heavy toroidal environment (Frank et al. 1995; Langer et al. 1999; Dwarkadas & Balick 1999) or fast non-spherical winds interacting with an isotropic environment (Frank et al. 1998). It has two attractive advantages: (i) it shows that a non-spherical fast wind impinging on a slow toroidal wind is able to produce the high-velocity outer parts of the equatorial ejecta observed around η Car (Smith et al. 2003a); and (ii) the choice of a lighter pre-outburst wind in our model, has resulted in a less dense toroidal halo around the large Homunculus nebula than in previous models, as required by the observations. [4]

It is noteworthy that, in numerical experiments where, instead of an initially non-spherical, a spherical outburst wind was injected into a toroidal pre-outburst slow wind with the asymmetry parameters α and β determined either from the observed large Homunculus expansion velocity distribution or given by the same values as those used by Frank et al. (1995) for a heavier toroid, have failed to produce simultaneously the shape of the large Homunculus and the equatorial ejecta. In these cases, the encounter of the shock fronts of the two winds first in the equatorial region and afterwards in the lateral regions of the outer bubble causes its fragmentation and spreading of the shell material at high latitudes, thus destroying the bipolar morphology (see Gonzalez et al. 2003). These results suggest that, in order to produce both the Homunculus bipolar morphology and the equatorial ejection from the winds interaction, these must be both intrinsically non-spherical (as in Figs. 1 and 2).

Although the interaction of the second outburst wind (assumed to be spherical) with its pre-outburst wind was able to produce the internal Homunculus, it has failed to develop internal equatorial ejecta in the simulation depicted in Figures 1 and 2. However, an appropriate combination of non-spherical wind parameters in this case similar to the one of the 1840s outburst, could also probably generate an internal equatorial ejection. In fact, recent UV images within 0.2 arcsec of the star, have revealed the existence of a little internal torus that may be related to the little Homunculus and may signify that a recurrent mass ejection with the same geometry as that of the Great Eruption may have occurred (Smith et al. 2003b, see also Gonzalez et al. 2003).

In order to simulate an experiment using a condition at the base of the η Car wind similar to the one $presently$ suggested by the observations (Smith et al. 2003a), we have also computed a model in which the non-spherical outburst wind of 1840s impinges on a slow pre-outburst wind with a larger density (and mass-loss rate) in the polar direction ($n \propto F_\theta$ in eq. [1]). We find that this scenario is unable to develop a narrow equatorial ejecta. This result suggests that the conditions at the wind base prior to the Great Eruption in the 1840s were probably not the same as the current ones.

Finally, we notice that, despite the high-resolution and the explicit time-dependent computation of the radiative cooling of the gas, our simulations, similarly to the radiative cooling models of Frank et al. (1998), have not revealed the for-

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[4]We note that the equatorial waist produced in the simulations is slightly thicker than the one observed. While observations indicate that the ejections are <0.4 times the diameter of the Homunculus lobes, in the simulations this is $\sim$0.6. We also note that the ratio of the length to the width of the two Homunculus is somewhat larger in the simulations. Both differences could be partially attributed to projection effects which were not considered here, and could be diminished with minor changes in the adopted parameters for the model.

mation of small fragments on the surface of the Homunculus, as those seen in Langer et al. (1999) simulations, which have resulted from Vishniac instabilities in the radiatively cooled shell long after the eruption. This is probably due to differences in the initial conditions between the two models. Nonetheless, a granular structure is effectively observed on the large Homunculus surface. Is is not improbable, however, that they have resulted from variability or instabilities in the winds *near* the surface of the star (Smith et al. 2003a). This question, as well as three-dimensional effects, will be addressed in future work.

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Fig. 1.— Gray-scale map of the density distribution (in log_{10} scale) for four different times in the evolution of the model. (a): t = 10 yr; (b) t = 60 yr; (c) t = 110 yr; and (d) t = 160 yr. The density (at the vertical scale on the right side of the figures) is in g cm^{-3}, and the x and y axis are in cm.

Fig. 2.— The same as in Figure 1d where it is depicted the present-day structure of the system with the inner and outer Homunculus nebulae, and the equatorial ejections. The density map has been rotated by an angle of 45°, like in the observations.

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